Geochemical and physical characterization of lithic raw materials in the Olduvai Basin, Tanzania

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Abstract:

The invention and proliferation of stone tool technology in the Early Stone Age (ESA) marks a watershed in human evolution. Patterns of lithic procurement, manufacture, use, and discard have much to tell us about ESA hominin cognition and land use. However, these issues cannot be fully explored outside the context of the physical attributes and spatio-temporal availability of the lithic raw materials themselves. The Olduvai Basin of northern Tanzania, which is home to both a wide variety of potential toolstones and a rich collection of ESA archaeological sites, provides an excellent opportunity to investigate the relationship between lithic technology and raw material characteristics. Here, we examine two attributes of the basin's igneous and metamorphic rocks: spatial location and fracture predictability. A total of 244 geological specimens were analyzed with non-destructive portable XRF (pXRF) to determine the geochemical distinctiveness of five primary and secondary sources, while 110 geological specimens were subjected to Schmidt rebound hardness tests to measure fracture predictability. Element concentrations derived via pXRF show significant differences between sources, and multivariate predictive models classify geological specimens with 75–80% accuracy. The predictive models identify Naibor Soit as the most likely source for a small sample of three lithic artifacts from Bed II, which supports the idea that this inselberg served as a source of toolstone during the early Pleistocene. Clear patterns in fracture predictability exist within and between both sources and rock types. Fine-grained volcanics show high rebound values (associated with high fracture predictability), while finer-grained metamorphics and coarse-grained gneisses show intermediate and low rebound values, respectively. Artifact data from Bed I and II suggest that fracture predictability played a role in raw material selection at some sites, but other attributes like durability, expediency, and nodule size and shape were more significant.

Keywords: Early Stone Age | Olduvai Gorge | Lithic raw materials | Schmidt rebound hardness | Portable X-ray fluorescence

Article:

1. Introduction

The study of raw materials has been embedded in analyses of the African Early Stone Age (ESA) for some time (Kleindienst, 1962; Stiles et al., 1974; Hay, 1976; Jones, 1979; Clark, 1980). Indeed, it is widely acknowledged that hominin lithic technology and ranging behavior cannot be fully understood unless the physical attributes and spatio-temporal availability of potential toolstones are considered. It appears that Oldowan tool-makers could be quite sensitive to variation in rock characteristics. While raw material choice was determined strictly, and at times necessarily, by local availability (Merrick and Merrick, 1978), many sites show evidence for non-random selection of rocks based on shape, dimensions, lithology, groundmass texture, and edge durability (Stout et al., 2005; Braun et al., 2009b; Harmand, 2009; Goldman-Neuman and Hovers, 2012). Acheulean peoples across Africa were equally variable, and perhaps more discerning, in their raw material choices, especially for rocks used to produce handaxes and other Large Cutting Tools (LCTs) (Sheppard and Kleindienst, 1996; Sharon, 2008; Harmand, 2009; Chazan, 2015; Wilkins, 2017; Leader et al., 2018). In terms of ranging behavior, ESA hominins gathered most of their raw materials during short forays (hundreds of meters to a handful of kilometers) to local conglomerates and/or surface outcrops (Braun et al., 2009a; Goldman-Neuman and Hovers, 2012; Kuman et al., 2018), although they did occasionally engage in longer distance treks (between 10 and 40 kilometers) to both primary outcrops and secondary sources (Braun et al., 2008, 2013). These findings have important—and contested—implications for our understanding of ESA hominin land use and cognitive abilities (Plummer, 2004; Schick and Toth, 2006; Braun and Hovers, 2009; Braun, 2012, 2013; Toth and Schick, 2018).

The Olduvai Basin of northern Tanzania (Fig. 1) is recognized among ESA site complexes for the diversity of its raw materials (Kyara, 1999: 342). Thanks largely to the late Richard Hay (1976), the area's bedrock geology and paleogeography, both of which are critical to determining the location of primary and secondary toolstone sources, are relatively well understood. The Olduvai Basin is a shallow, hydrologically-closed depression that, during Bed I and II times, ca. 2.0 to 1.3 Ma, contained a saline and alkaline playa lake of fluctuating size (Hay, 1976; Hay and Kyser, 2001; Ashley and Hay, 2002). Olduvai's Early Pleistocene hominin populations could access primary volcanic outcrops from one of the four major volcanos that bound the basin to the east and south: Lemagurut (aka Lemagrut), Satiman (aka Sadiman), Ngorongoro, and Olmoti. Engelosin, a volcanic neck some eight kilometers north of Olduvai Gorge, was also available as a primary source of extrusive material. In some areas, lava flows interbed directly with Bed I sediments and, thus, were available directly on-site for immediate use by hominins (Potts, 1988). The metamorphic basement rocks that outcrop across the basin as scattered inselbergs provided other primary sources of toolstone. Small chert nodules, which formed within the lacustrine sediments of paleolake Olduvai, were sporadically accessible during Bed II times as isolated pieces or within chert-bearing horizons. Nearly all these sedimentary, igneous, and metamorphic materials could also be found throughout the central basin within redeposited sediments.

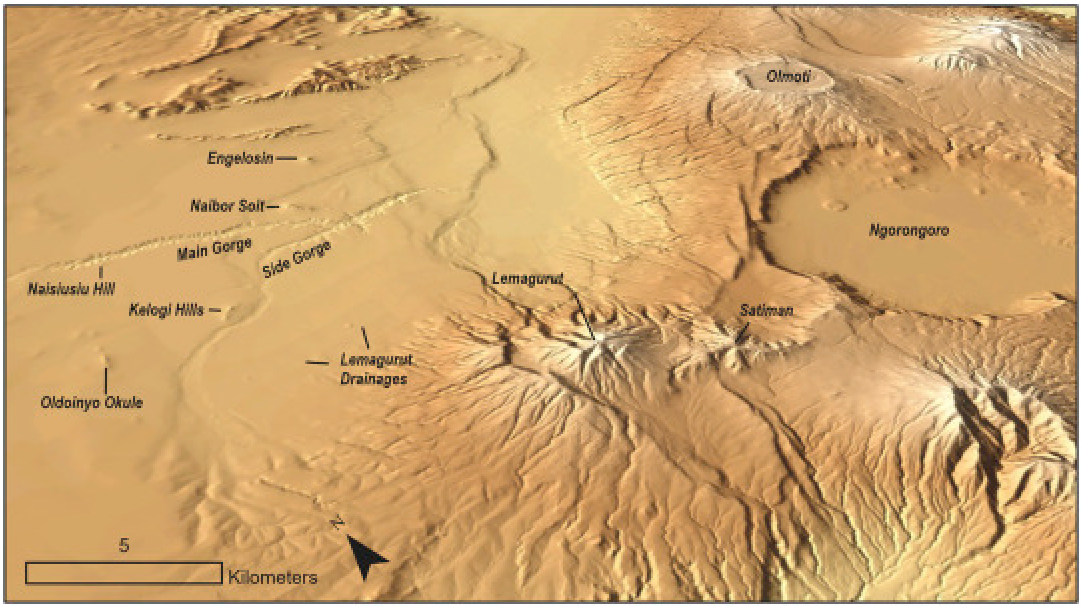

Figure 1. Map of the Olduvai Basin with major landforms.

Mary Leakey (1967, 1971, 1975) was the first to consider systematically the impact of raw material on technological variation in the Olduvai ESA lithic assemblages, observing that so-called "light duty" tools (e.g., utilized flakes) and debitage tend to be flaked from quartz, quartzite, and chert, whereas volcanic rocks dominate the "heavy duty" tools (e.g., choppers, polyhedrons). She speculates (1967: 421) that this pattern "probably indicates a deliberate selection of material for different purposes, and may be due, not only to the suitability of various rocks, but also to accessibility." As we outline below, the two factors that Leakey identifies—suitability and accessibility—inform nearly all subsequent work on the Olduvai Basin's raw materials.

Invoking raw material suitability as Leakey does of course begs the question: suitable for what? While she leaves this largely unanswered (see M.D. Leakey, 1967: 422 for a cursory remark on the utility of quartz flakes), other analysts working with the Olduvai lithic assemblages identify several physical attributes that may influence the suitability of a raw material. A series of tool replication and use experiments by Jones (1979, 1980, 1981, 1994) demonstrates the importance of raw material size, shape, mechanical properties, and edge durability to the final form and butchery efficiency of LCTs and other lithic types. Later experimental studies with the Olduvai Basin's raw materials nevertheless identify (as does Jones himself) a rock's "fracture mechanics," "fracture properties," "knappability," "flakability," "quality," and/or "flaking properties" to be of particular importance (Kimura, 1997; Kyara, 1999; Tactikos, 2005; Reti, 2013). Our impression is that these terms, though not identical in their application, are explicitly or implicitly meant to describe the fracture predictability of a rock and, more specifically, the degree to which a rock permits the controlled and consistent removal of complete flakes (e.g., Kyara, 1999: 300, 309). It is in this sense that we employ the term "suitability" here: highly suitable rocks fracture predictably and, thus, are amenable to the production of complete flakes, whereas less suitable rocks fracture less predictably and are correspondingly less amenable to the production of complete flakes.

Most assessments of raw material suitability among the Olduvai lithic assemblages are based largely on informal impressions or experimental parameters that are difficult to replicate (Jones, 1994; Kimura, 1997; Kyara, 1999), and the distinctions themselves are often converted into imprecise categories (e.g., high quality vs. low quality; Kimura, 2002; Blumenschine et al., 2008) that may be insensitive to the preferences of ESA hominins. Although we appreciate the position of those like Kimura (1997: 32), who doubts that Olduvai's ESA knappers “were aware of subtle mineralogical differences of rocks,” it is hazardous to simply assume that hominins grouped raw materials into the broad categories typically employed by paleoanthropologists. Such assertions can be tested with objective, quantitative measures of raw material suitability. In the absence of such tests, concepts like suitability, or any other culturally meaningful rock attribute, will be difficult to operationalize not only within and among the Olduvai assemblages but across studies of other ESA archaeological complexes.

Leakey's other variable, accessibility, is largely a question of where and when a raw material is available on the landscape. As mentioned above, potential toolstones were scattered across the paleo-Olduvai Basin in both primary and secondary forms, so while some rocks could be procured essentially on-site, others required journeys of several kilometers (Hay, 1976). The temporal availability of raw materials to hominins living around the paleolake varied significantly as well. During high lake stands, for example, Engelosin and some metamorphic inselbergs were probably surrounded by water and potentially inaccessible (Hay, 1976). Changes in fluvial dynamics also influenced the transportation, deposition, and exposure over time of cobbles suitable for tool manufacture.

There is little doubt that the location of raw materials and their spatial proximity to other affordances like water, shade, animal carcasses, plant foods, and predators conditioned hominins’ exploitation of rocks in the paleo-Olduvai Basin (Hay, 1976; Potts, 1988, 1991; Peters and Blumenschine, 1995; Blumenschine and Peters, 1998; Blumenschine et al., 2005, 2007; 2008, 2009; 2012; Tactikos, 2005). However, building and testing models of these relationships is predicated on secure linkages between artifacts and their original sources. Those interested in sourcing the artifacts from Olduvai most commonly rely on macroscopic comparisons with hand samples collected at currently observable sources and/or the detailed lithological and mineralogical descriptions of Hay (1976: 11–13) and Kyara (1999: 115–127) (M.D. Leakey, 1971, 1994; Jones, 1994; Blumenschine and Peters, 1998; Kimura, 1999, 2002; de la Torre and Mora, 2005; Blumenschine et al., 2008, 2012; Diez-Martín et al., 2009; Santonja et al., 2014; Rubio-Jara et al., 2017; McHenry and de la Torre, 2018). Others supplement this information with petrographic and geochemical data from the same sources (Stiles et al., 1974; Mollel, 2007; Sánchez Yustos et al., 2012; Abtosway, 2018; McHenry and de la Torre, 2018; Bello-Alonso et al., 2019; Favreau, 2019).

Some authors also choose to collapse artifact raw materials into a few classes (e.g., lavas/volcanic vs. quartz/quartzite) for purposes of analysis even though the rocks within these classes occur at spatially discrete and, in some cases, very distant, sources (e.g., Blumenschine and Peters, 1998; Blumenschine et al., 2012). Such consolidation is not unreasonable given issues of sample size and presumed similarities in flaking characteristics among closely related rock types (e.g., Kimura, 1997: 32–33). However, the potential existence of as-yet undocumented sources (Tactikos, 2005: 140–141; Diez-Martín et al., 2009: 288) and the difficulty of using macroscopic features to determine rock type and the specific source from which an artifact actually derives (Kyara, 1999: 118; de la Torre and Mora, 2005: 207; Santonja et al., 2014: 187) also hinder our ability to treat rock types and their associated sources as individual units of analysis.

The degree to which metamorphic and sedimentary artifacts from Olduvai are (or could be) incorrectly assigned to sources based on readily observable macroscopic characteristics is currently unknown. However, McHenry and de la Torre (2018) report that of 29 igneous specimens excavated from Bed II that were subjected to both hand sample and geochemical analysis, eight (27.6%), most of them fine-grained and weathered, were misclassified based on hand sample criteria. Such misclassifications can potentially jeopardize the attribution of artifacts to particular sources and complicate attempts to disentangle distance-decay effects (Blumenschine et al., 2008, 2012) from other factors like cultural preference (de la Torre and Mora, 2005: 208). It is within this context that we more fully explore Leakey's ideas of suitability and accessibility among Olduvai's raw materials through mechanical tests of rebound hardness and portable X-ray fluorescence estimates of element concentrations.

2. Materials and methods

2.1. Raw material sources

Our analyses focus on five metamorphic sources, all of which are primary, and two igneous sources, one primary and one secondary.

2.2. Metamorphic sources

Naibor Soit, Naisiusiu Hill, Shifting Sand (aka Endonyo Osunyai), Oldoinyo (aka Endonyo) Okule (aka Lekule), and the Kelogi (aka Keloki) Hills are metamorphic inselbergs situated within several kilometers of Olduvai's archaeological sites (Fig. 1). Naibor Soit, which lies closest to the gorge's well-known junction sites (e.g., FLK, FLK North) and is thought to be a major source of toolstone, actually outcrops as three distinct hills: the Main Hill, Manyata Hill (aka Oittii), and the Southern Outlier (aka little Naibor, Naibor ndogo, or Endoinyo Osokoni) (Kyara, 1999: 141–143; Favreau, 2019: 81–83). We use the term Naibor Soit to refer to all three hills collectively. The materials at these five outcrops are well-differentiated and quartz-rich, although they contain a variety of other minerals, chiefly mica, and sometimes exhibit clear foliation (Fig. 2). The Kelogi Hills and Naisiusiu Hill possess the richest and most diverse mineralogies and, consequently, the least quartz by volume. The texture of rocks from these outcrops also ranges widely, from cryptocrystalline (Oldoinyo Okule) to coarse-grained (Kelogi Hills). The variability in composition among and within these outcrops is the result of the complex history of the Tanzanian Craton, which dates to the Archaean (Dawson, 2008; Begg et al., 2009).

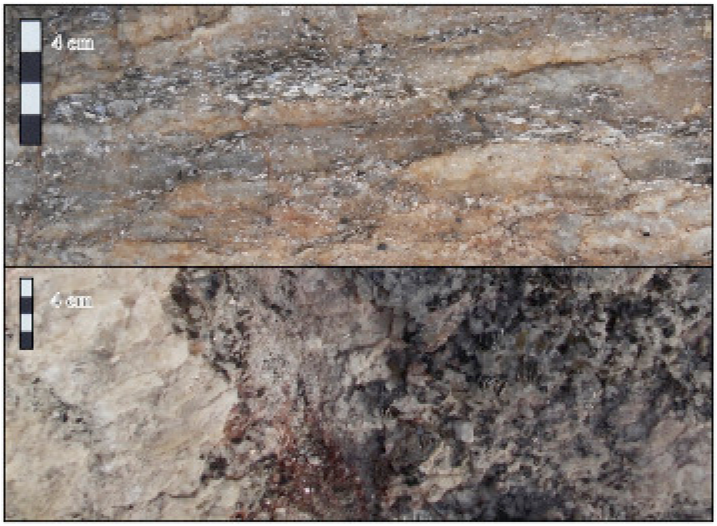

Figure 2. (Top) Foliated quartz and muscovite at Shifting Sand; (Bottom) Diversity of minerals present at Naisiusiu Hill, including quartz, muscovite, garnet, and plagioclase.

While archaeologists working in the Olduvai Basin uniformly designate the rocks of the Kelogi Hills as gneiss, there is less agreement on the characterization of the other outcrops. Following Pickering (1958) and, later, Hay (1976), some workers refer to the silica-rich toolstones from Naisiusiu Hill, Shifting Sand, Oldoinyo Okule, and particularly Naibor Soit as quartzite (e.g., M.D. Leakey, 1971; Jones, 1979; Blumenschine et al., 2008; Santonja et al., 2014), while others identify them simply as quartz (e.g., Kimura, 1999; Mora and de la Torre, 2005; Diez-Martín et al., 2011). More recent geological work on the Tanzanian Craton reveals that these inselbergs are too metamorphically evolved to be quartzite and, thus, are probably best characterized as resistant, quartz-rich remnants of heavily weathered granulites (Dawson, 2008; Begg et al., 2009), which is the label we adopt here. Nevertheless, we think it is reasonable for Olduvai lithic artifacts presumably harvested from these outcrops and flaked largely or exclusively from their quartz constituents to be referred to as “quartz” artifacts.

2.3. Igneous sources

Our igneous samples are drawn from two sources: Engelosin and Lemagurut. The small, isolated volcanic cone of Engelosin is a primary source of green, fine-grained phonolites. Lemagurut is a heavily dissected shield volcano that lies along the southern edge of the Olduvai Basin. Its lavas are composed largely of medium- to fine-grained basalts, although other rock types (e.g., hawaiite, mugearite) appear as well (Mollel and Swisher III, 2012). The Lemagurut samples used in this study derive from fluvially transported blocks found within the ephemeral channels that drain the mountain's northeastern slopes.

2.4. X-ray fluorescence analysis

The use of X-ray fluorescence, or XRF, to analyze the elemental composition of stone has a long history in archaeology (Shackley, 2011). Obsidian, which typically forms from single, spatially discrete, and homogenous lava flows, is an especially popular subject of XRF analysis (Carter, 2014). XRF and other petrochemical techniques have been used in attempts to characterize several of the igneous, metamorphic, and sedimentary rocks within the Olduvai Basin (Stiles et al., 1974; Mollel, 2007; Sánchez-Yustos et al., 2012; Abtosway, 2018; McHenry and de la Torre, 2018; Favreau, 2019). Our focus here is the identification of geochemical clusters among the granulite outcrops of Naibor Soit, Shifting Sand, Naisiusiu Hill, and Oldoinyo Okule. The descriptions of Hay (1976) and others (Jones, 1994: 256; Kyara, 1999: 120–122, 141–148, 151–154; Tactikos, 2005: 69–70) identify several macroscopic differences among these sources. While our experience confirms these modal distinctions, there is nonetheless a good deal of intra-source variation, so some specimens can be difficult to distinguish, especially those that are small and/or whose original shape (e.g., block vs. cobble) cannot be determined (cf. Santonja et al., 2014: 187). (Rocks from the Kelogi Hills, on the other hand, are quite distinct, and most are easily distinguishable, even in hand samples.)

Like many metamorphic rocks, granulites form under a variety of circumstances and can thus, as Pitblado et al. (2008: 745) put it for quartzite, "yield very similar or very different elemental signatures" within and between outcrops. This potential volatility in composition can both hinder and facilitate the identification of distinct geochemical groups through XRF. In some cases, metamorphic rocks are too chemically homogenous over large areas or too chemically heterogeneous within individual outcrops to be usefully distinguished, while in others, chemical signatures are patterned enough to effectively isolate discrete clusters (Church, 1996; Schneider, 2007; Pitblado et al., 2008; Blomme and Degryse, 2012; Sciuto et al., 2019). Previous attempts to source metamorphic rocks with XRF employ a variety of lab-based and portable instrumentation. Our analyses rely on commercial handheld XRF technology (portable XRF, or pXRF), which permits rapid, non-destructive data collection.

For some, pXRF lacks the analytical rigor of more traditional lab-based approaches. The use of rock samples with non-standard sizes and complex topographies and a reliance on factory-set corrections and calibrations to derive elemental concentrations are seen as particularly problematic (Frahm, 2013a; Speakman and Shackley, 2013). Though not unfounded, these critiques revolve largely around the correspondence (or lack thereof) of pXRF element concentrations to "true" values generated through lab-based protocols. Such geochemical accuracy is certainly desirable in some cases, but our goal is *archaeological* accuracy. In other words, can pXRF produce data that accurately classify a rock to the source from which it is known to derive? If so, we have confidence that pXRF produces valid data: that is, element concentrations that can distinguish geological sources in space and link isolated rocks to those sources (Frahm, 2013a, 2013b). Two other issues, repeatability and reproducibility, are also of critical importance. Frahm (2012: 168), who follows the National Institute of Standards and Technology (NIST), defines the former as "the agreement between sequential measurements under identical conditions" and the latter as the "agreement when observers, conditions, or instruments change or after time has passed." Here, we evaluate the validity, repeatability, and geochemical and archaeological accuracy of our pXRF-based element concentrations and rock-to-source assignments. The reproducibility of these data awaits additional analyses with different instruments, observers, and conditions.

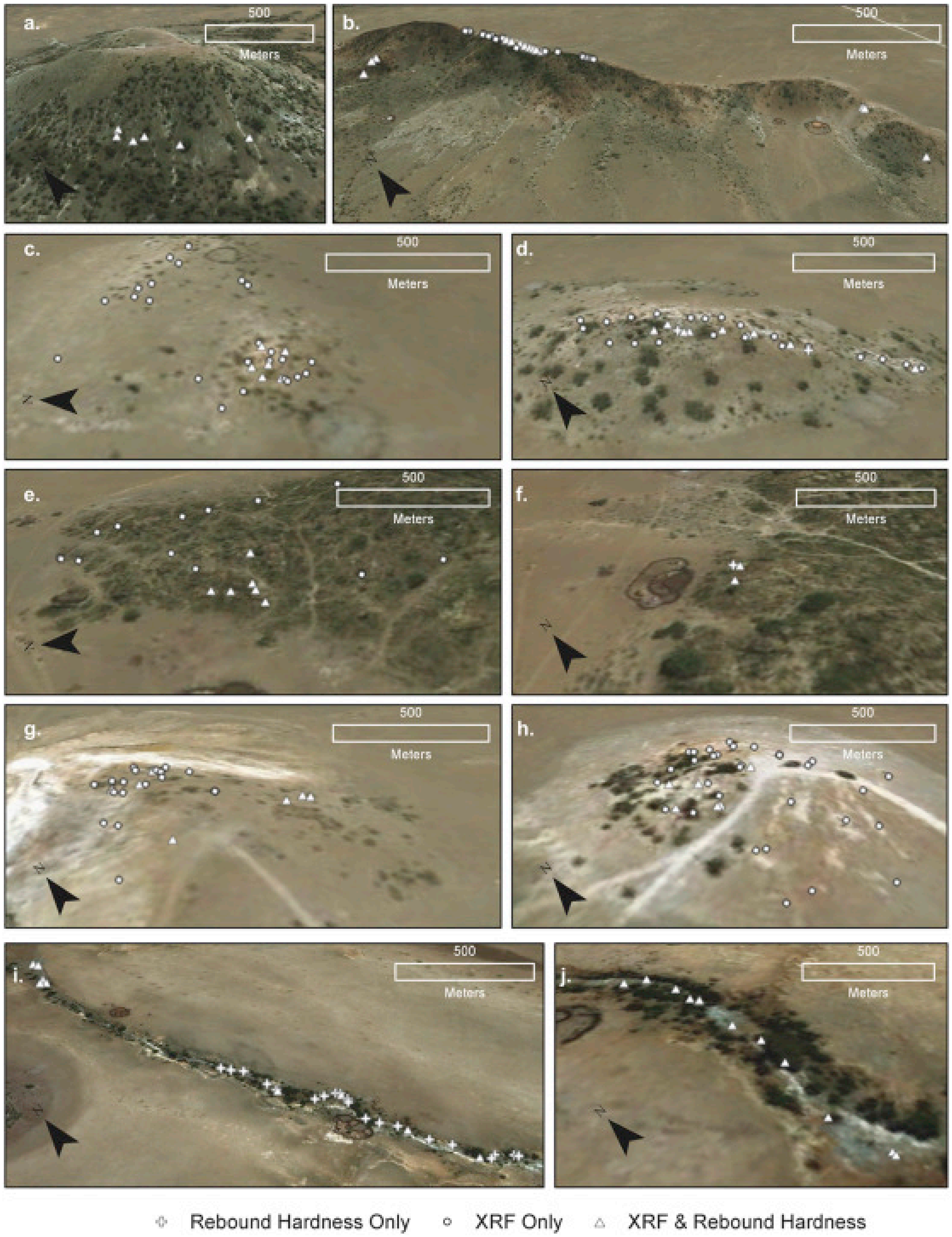

Figure 3. Location of rebound hammer and pXRF samples at each source. (a) Engelosin; (b) Naibor Soit Main Hill; (c) Naibor Soit Manyata Hill; (d) Naibor Soit Southern Outlier; (e) and (f) Kelogi Hills; (g) Naisiusui Hill; (h) Shifting Sand; (i) and (j) Lemagurut drainages.

We flaked rock specimens directly from outcrops with a rock hammer. Each specimen's geolocation was recorded with both handheld GPS (±3 m) and DGPS (±1 cm) devices (Fig. 3). While a concerted effort was made to sample the entire spatial extent of each outcrop, some areas were inaccessible due to sediment build-up and/or dense vegetation. We were also careful to select only visually quartz-rich specimens from among the granulite outcrops for pXRF analysis. Naisiusiu Hill in particular contains a significant volume of rock with non-quartz minerals that were not included in the analysis. This protocol resulted in the collection of 244 specimens (Table 1). We also tested quartz-rich metamorphic artifacts from BK East, a site on the south wall of the side gorge that preserves lithics and butchered bone within the sediments of an ancient braided river system. Preliminary stratigraphic correlations suggest that the BK East deposits lie within upper Middle Bed II, somewhat higher in the sequence than SHK (ca. 1.5Ma; Diez-Martín et al., 2014) and just below BK (ca. 1.35Ma; Domínguez-Rodrigo et al., 2013). A total of five artifacts were analyzed, although only three (Fig. 4, Fig. 5, Fig. 6) can be sourced (see below). The artifacts are all too small to determine their original form (block/slab vs. cobble) definitively.

Table 1. Sample sizes for pXRF and rebound hardness by outcrop.

Outcrop	XRF sample size	Rebound hardness sample size
Naibor Soit-Main Hill (NS-M)	31	14
Naibor Soit-Manyata Hill (NS-MH)	30[a]	6
Naibor Soit-Southern Outlier (NS–SO)	30	11
Shifting Sand (SS)	38	6
Naisiusiu Hill (NH)	27	7
Oldoinyo Okule (OL)	30	15
Kelogi Hills (KG)	30	11
Engelosin (EN)	7	7
Lemagurut Drainages (LD)	21	48
Total	244	110

[a] Two samples not included in statistical analysis (see text for discussion).

Figure 4. Dorsal (left) and ventral (right) views of a retouched quartz flake from BK East (artifact BKE1). Scale bar = 1 cm.

Figure 5. Quartz core fragment from BK East (artifact BKE2). Scale bar = 1 cm.

Figure 6. Dorsal (left) and ventral (right) views of notched quartz flake fragment from BK East (artifact BKE3). Scale bar = 1 cm.

After shipment back to the United States, pXRF analyses were conducted with an Innov-X Delta Classic Environmental Analyzer equipped with a 4W Au anode X-ray tube and a Si-PIN diode detector. All analyses were performed while the instrument was docked into a stable, hands-free test stand. An unweathered, non-cortical surface free of sediment matrix was placed over, and completely covered, the detector window. To maximize X-ray counts and the number of detected elements, each specimen was measured for 360 s using all three of the instrument's beams (120 s/beam). After an initial energy scale calibration test with a factory issued metal coin of known composition, the following protocol was observed:

1. A powdered sample of Standard Reference Material (SRM) 2702 with elemental concentrations certified by NIST was measured.
2. Four geological/archaeological specimens were then measured.
3. The fifth geological/archaeological specimen in a series was measured five times (that is, five consecutive 360s cycles) without being moved or reoriented.
4. After the fifth geological/archaeological specimen was measured, the SRM 2702 sample was measured once again, which initiated the next series of measurements.
5. Element concentrations were derived with the Compton Normalization correction model and the factory-set "Soil Environmental" calibration.

2.5. Rebound hardness analysis

Lithic analysts recognize the need for replicable, ratio-scale measures of raw material suitability (however that is defined), and many see promise in the various mechanical tests developed by material scientists (for excellent reviews and recent applications, see Moník and Hadraba, 2016; Rodríguez-Rellán, 2016). Kyara's (1999) use of the "Aggregate Impact Value" test to assess rock strength is a notable example within the context of the Olduvai raw materials. Here, we employ a rebound hardness test as a proxy for fracture predictability. Three traits often characterize rocks that fracture predictably: little or no crystalline macrostructure, few impurities, and small average crystal size (Crabtree, 1967; Luedtke, 1992; Domański et al., 1994; Brantingham et al., 2000). Rocks with more homogenous structures, it seems, are better able to resist strain (i.e., they are stronger) and deformation (i.e., they are more elastic), both of which encourage stable, and thus predictable, impact response and fracture propagation (Cotterell et al., 1985; Cotterell and Kamminga, 1987). Rock strength and elasticity can be estimated with a rebound hardness test, the most common of which relies on a Schmidt Hammer. This handheld device fires a spring-loaded plunger against the surface of a material whose ability to absorb energy is reflected by the degree of plunger recovery ("rebound") after impact (Goudie, 2006). Hard and elastic materials return high rebound readings, whereas softer, less elastic materials return low rebound readings. Importantly, close correspondence exists between rebound hardness and various indicators of raw material suitability, including (1) step fracture rates and informal assessments of "flakability" (Noll, 2000: 98, 263), (2) the frequency of impurities (Braun et al., 2009b: 1610), and (3) experimental work with the Olduvai raw materials themselves (see below).

Rebound hardness was measured with a Proseq N-Type RockSchmidt Rebound Hammer (Fig. 7). We tested in situ exposures at primary sources, while specimens from secondary sources were drawn from among the numerous basalt blocks at the foot of Lemagurut (Table 1). As with the pXRF specimens, geolocations were recorded with both handheld GPS and DGPS devices (Fig. 3). (Many pXRF and rebound test specimens have the same geolocation information because pXRF specimens were often detached from an exposure or block after a rebound test was performed.) A total of 110 specimens were subjected to rebound hardness tests (Table 1). To ensure a full and accurate transfer of rebound energy, our specimen selection and measurement protocol was guided by the recommendations of the International Society of Rock Mechanics (Aydin, 2009):

1. Every effort was made to select surfaces that were dry, smooth, free of visible cracks, and unweathered or only lightly weathered.
2. All specimens were at least (and, in most cases, much more than) 10 cm in thickness at the points of hammer impact.
3. All specimens remained stationary during impact. This was not an issue with in situ outcrops, and we only selected from among the free-standing basalt blocks those with enough mass to minimize movement during hammer impacts.
4. The hammer's plunger was positioned perpendicular to the tested surface during impact events.
5. A total of 20 rebound measurements, each spaced ~2 cm apart, were taken on each specimen. The resulting values were averaged to derive the specimen's rebound hardness.
6. All impacts occurred at least 2 cm from the edge of a test specimen.
7. The plunger and spring were replaced after every 100 impacts.
8. The device was sent to Proseq for cleaning and full calibration after each field season.

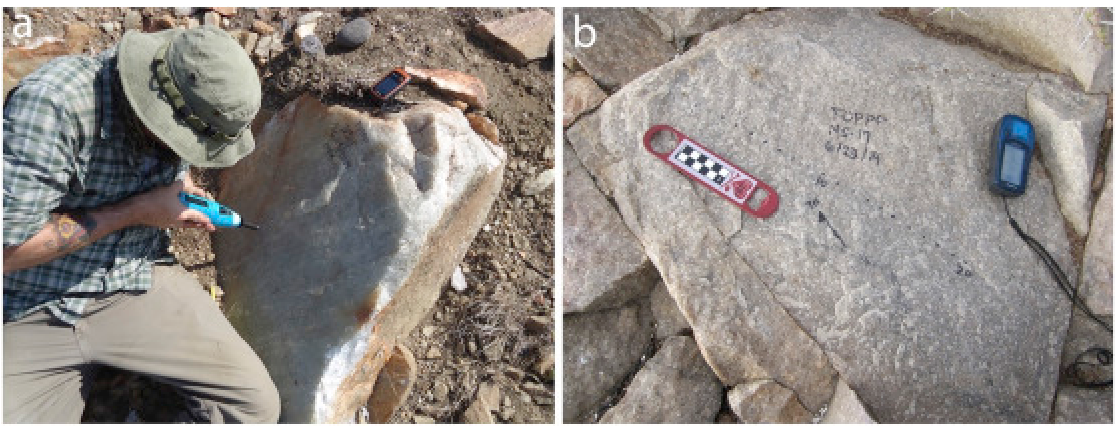

Figure 7. The use of the rebound hammer on in situ exposures at Naibor Soit. (a) the device is pressed against the tested surface until a spring-loaded plunger is released to impact the material; (b) a total of 20 rebound measurements, each spaced ~2 cm apart (as marked by the black points), is taken on each specimen.

2.6. Data pre-processing and statistical analysis

Our pXRF instrument is calibrated to detect a specific array of elements, and only a handful of those could be detected in all or most of the Olduvai granulite rock specimens. Table 2 summarizes the detection rate by element for the granulite samples. To minimize the number of missing values and maximize the predictive performance of the statistical models, we concentrate our analysis only on those elements with detection rates >75%. The six elements that meet this criterion, potassium (K), titanium (Ti), iron (Fe), strontium (Sr), yttrium (Y), and zirconium (Zr), serve as the predictor variables for the models described below. All statistical analyses are conducted within the R version 3.5.3 environment (R Core Team, 2019).

Two of the 186 granulite specimens are missing values for five out of the six elements and are therefore not included in the statistical analyses. Of the remaining 184 specimens, 55 have missing data for one element, and two of those 55 have missing data for two elements. We treat these missing values as censored data; i.e., the element is present, but could not be measured precisely enough for the instrument to report a value. We estimate these missing values in one of two ways. For those specimens subjected to duplicate runs (n = 7), we simply replace the missing value with the mean value of the duplicates. The missing values for the remaining specimens (n = 48) are replaced with the mean of the four closest (as determined in two-dimensional space by the "Distance Matrix" function in QGIS) specimens with measured (rather than estimated) values.

Table 2. List of factory-set elements in pXRF "Soil Environmental" calibration and their detection rates for the 186 granulite rock specimens.[a].

Element	Missing values	Non-detect rate	Detect rate
Fe	**0**	**0.0%**	**100.0%**
Ti	**2**	**1.1%**	**98.9%**
Zr	**2**	**1.1%**	**98.9%**
K	**5**	**2.7%**	**97.3%**
Sr	**17**	**9.1%**	**90.9%**
Y	**41**	**22.0%**	**78.0%**
Rb	51	27.4%	72.6%
V	57	30.6%	69.4%
Ca	93	50.0%	50.0%
Mn	120	64.5%	35.5%
Cr	122	65.6%	34.4%
Ni	146	78.5%	21.5%
Nb	154	82.8%	17.2%
Pb	160	86.0%	14.0%
P	167	89.8%	10.2%
Sn	173	93.0%	7.0%
U	175	94.1%	5.9%
As	178	95.7%	4.3%
S	180	96.8%	3.2%
Zn	180	96.8%	3.2%
Cu	181	97.3%	2.7%
Bi	183	98.4%	1.6%
Ag	186	100.0%	0.0%
Au	186	100.0%	0.0%
Ba	186	100.0%	0.0%
Cd	186	100.0%	0.0%
Cl	186	100.0%	0.0%
Co	186	100.0%	0.0%
Hg	186	100.0%	0.0%
Mo	186	100.0%	0.0%
Sb	186	100.0%	0.0%
Se	186	100.0%	0.0%

[a] Elements with detection rates >75% are in bold.

We first explore the raw granulite pXRF data through univariate tests. Because these data are significantly positively skewed and do not exhibit homogeneity of variance, we use Mood's median test and its associated pair-wise post-hoc tests in R's "RVAideMemoire" package (Hervé, 2019). A multivariate predictive modeling approach is then used to assess the geochemical distinctiveness of Olduvai's granulite outcrops and to evaluate the validity of rock-to-source assignments. A host of options are available (e.g., Kuhn and Johnson, 2013; Lantz, 2015), and here we compare the performance of Linear Discriminant Analysis (LDA), Mixture Discriminant Analysis (MDA), Support Vector Machine (SVM) (here we use a radial basis kernel function), *k*-

Nearest Neighbor (kNN), and Random Forest (RF). These techniques are not only powerful but tackle classification both linearly and nonlinearly with a wide variety of algorithmic approaches, an important consideration if we want to gauge fully our ability to distinguish granulite outcrops in the Olduvai Basin. Some of these models are sensitive to redundant predictors, but multicollinearity does not appear to be a significant issue in this case (Table 3). We use R's "caret" package (Kuhn, 2008, 2019) to build and evaluate the predictive models. Prior to model construction and training, we perform a Box-Cox transformation and then center and scale the distributions for all six elements to create a common scale across variables (mean = 0; standard deviation = 1).

Table 3. Coefficient of determination (r^2) matrix by element for granulite rock specimens.[a].

		Element					
		K	**Ti**	**Fe**	**Sr**	**Y**	**Zr**
Element	K	1.00					
	Ti	0.17	1.00				
	Fe	0.10	0.54	1.00			
	Sr	0.10	0.28	0.28	1.00		
	Y	0.00	0.18	0.06	0.26	1.00	
	Zr	0.05	0.41	0.16	0.30	0.30	1.00

[a] Correlations conducted on transformed data.

The first step in the modeling process is to split the pXRF data into a training set and a testing set. The training set (70% of the total sample; n = 130) is used to construct, train, and tune the predictive models based on the elemental compositions of samples known to derive from a particular source. The specimens in the testing set (30% of the total sample; n = 54) are then assigned to a source by the predictive model. Because the testing set, which is also composed of specimens of known derivation, is held out of the model-building process entirely, it serves as an unbiased evaluation of the models' predictive performance. Random stratified sampling is used to derive the training/testing split to ensure that the relative frequencies of specimens within each of the sources is similar in both sets.

Predictive models possess parameters that can be modified to optimally fit the structure of a dataset and enhance classification accuracy. These "tuning parameters" are identified by resampling the training set via 10-fold cross-validation. This routine first divides the training set into 10 subsets (referred to as "folds") of roughly equal size. Each of these subsets is iteratively held out while the model is trained on the remaining nine subsets. The source of the specimens within each held-out subset is then predicted to derive a cross-validation accuracy. This is repeated 10 times across a range of candidate tuning parameters. The tuning parameters that result in the highest classification accuracy (as estimated by Cohen's Kappa, which corrects the observed raw accuracy by accounting for correct predictions by chance) are used to construct the final predictive models. Other important measures of model performance are the proportion of specimens classified by the model to the outcrop from which they do, in fact, derive ("sensitivity" or "true positive rate"), the proportion of specimens correctly classified by the model as not deriving from a particular outcrop ("specificity" or "true negative rate"), and the mean of these values ("balanced accuracy").

The distributions of rebound hardness deviate from normality as well, although we prefer to work with these values in their original, and potentially behaviorally meaningful, units. We again use Mood's median test and its associated pair-wise post-hoc tests, which do not assume normality or variance homogeneity (both of which are violated by the rebound hardness distributions), to track patterns across outcrops and raw material types.

3. Results

3.1. Geochemical accuracy of pXRF data

Table 4 compares the certified element concentrations for the NIST 2702 reference and the mean of 55 runs of pXRF-derived element concentrations. The percent error rates range from a high of 37.1% to a low of 2.0%. The two elements with concentrations certified by NIST and measured by the pXRF in the granulite samples, titanium and strontium, show values of 22.0% and 2.0%, respectively.

Table 4. Reported and pXRF-derived element concentrations for NIST 2702[a].

Element	NIST 2702 certified value (ppm)	pXRF mean (ppm)	pXRF standard deviation	%Error
K	20540	25067.2	480.3	22.0%
Ti	8840	10605.3	165.0	20.0%
V	357.6	224.8	9.1	37.1%
Cr	352	384.6	13.6	9.3%
Mn	1757	1955.9	42.9	11.3%
Ni	75.4	54.5	14.1	27.8%
Zn	485.3	420.6	8.8	13.3%
As	45.3	41.4	3.1	8.7%
Rb	127.7	134.4	2.7	5.2%
Sr	119.7	117.3	2.6	2.0%
Pb	132.8	128.1	4.0	3.5%
Th	20.51	20.0	3.1	2.3%

[a] Includes only those elements with concentrations both certified by NIST and measured by the pXRF.

3.2. Repeatability of pXRF data

Table 5 summarizes the percent standard deviation across the six predictor variables for the 37 granulite specimens that were measured five consecutive times. Most elements cluster in the 3–7% range, although yttrium shows slightly elevated values. Fig. 8, Fig. 9, Fig. 10, Fig. 11, Fig. 12, Fig. 13 break these data down by source. While a majority of the specimens return values of <10%, those from the Naibor Soit hills (combined in these figures) show more variation in repeated measurements, especially for yttrium and strontium.

Table 5. Percent standard deviation by element for repeated pXRF measurements of granulite rock specimens.

	% Standard deviation	
Element	**Mean**	**Median**
K	5.2	4.1
Ti	5.2	3.9
Fe	5.8	3.4
Sr	7.4	6.6
Y	13.4	12.3
Zr	3.1	2.8

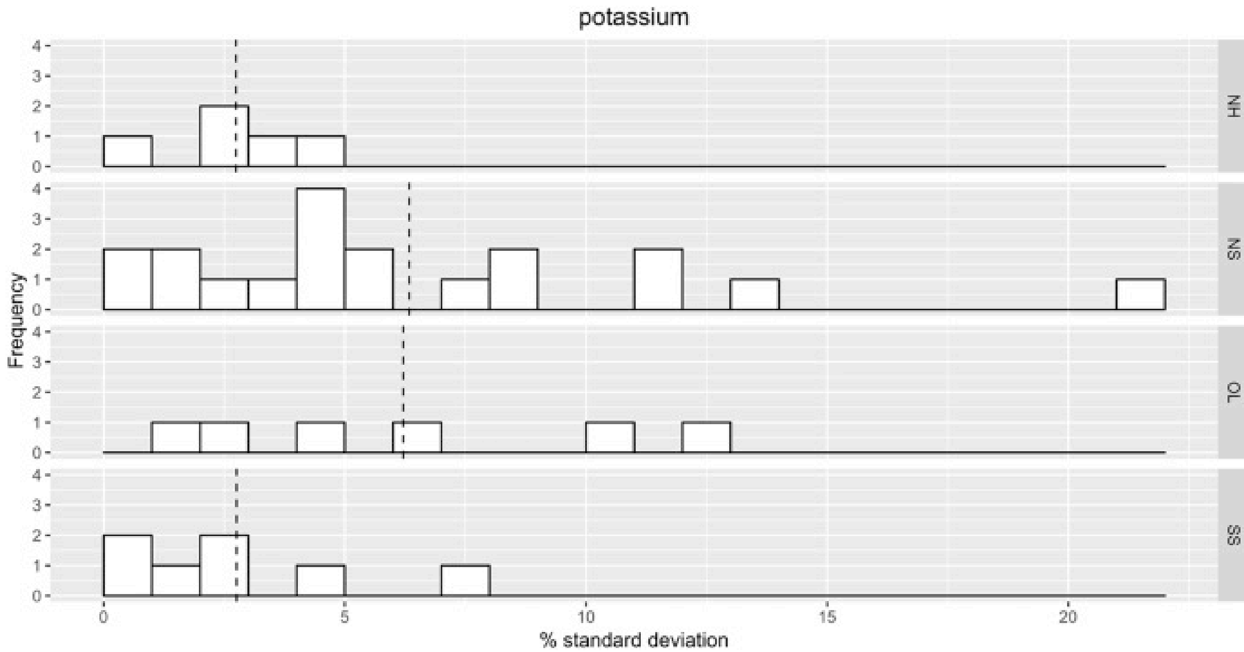

Figure 8. Histograms of % standard deviation for potassium by granulite outcrop. Abbreviations: NH = Naisiusiu Hill; NS = Naibor Soit; OL = Oldoinyo Okule; SS = Shifting Sand. Vertical dashed line indicates the mean value for each outcrop.

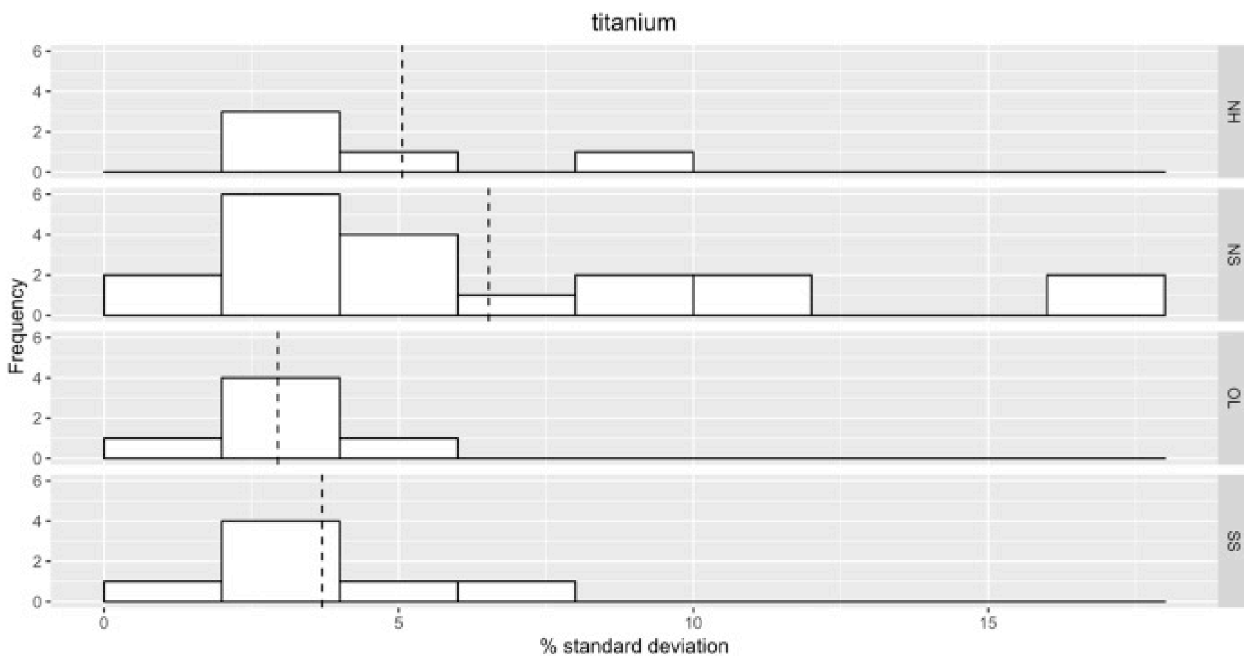

Figure 9. Histograms of % standard deviation for titanium by granulite outcrop. Abbreviations: NH = Naisiusiu Hill; NS = Naibor Soit; OL = Oldoinyo Okule; SS = Shifting Sand. Vertical dashed line indicates the mean value for each outcrop.

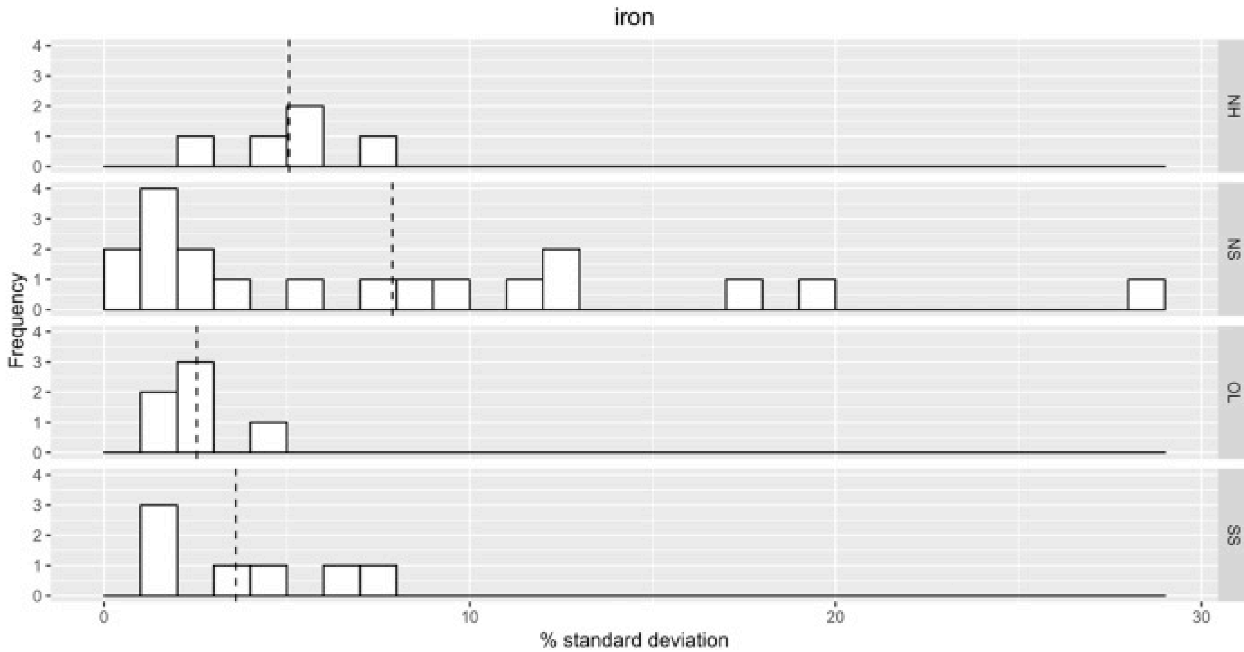

Figure 10. Histograms of % standard deviation for iron by granulite outcrop. Abbreviations: NH = Naisiusiu Hill; NS = Naibor Soit; OL = Oldoinyo Okule; SS = Shifting Sand. Vertical dashed line indicates the mean value for each outcrop.

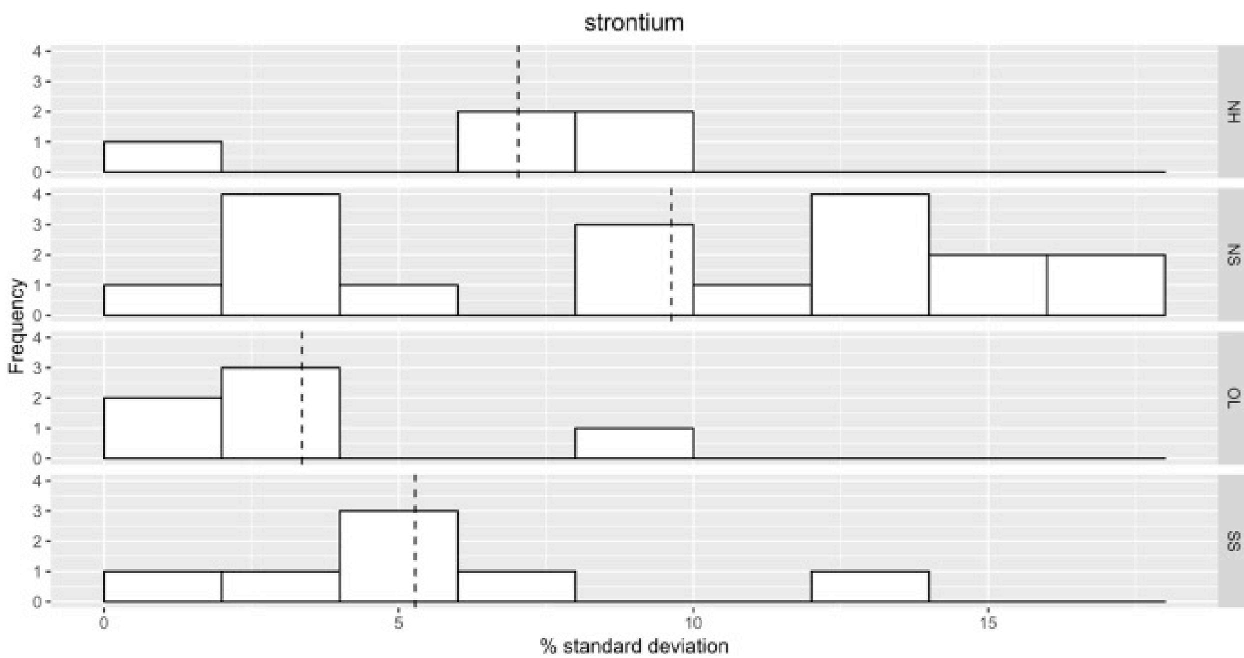

Figure 11. Histograms of % standard deviation for strontium by granulite outcrop. Abbreviations: NH = Naisiusiu Hill; NS = Naibor Soit; OL = Oldoinyo Okule; SS = Shifting Sand. Vertical dashed line indicates the mean value for each outcrop.

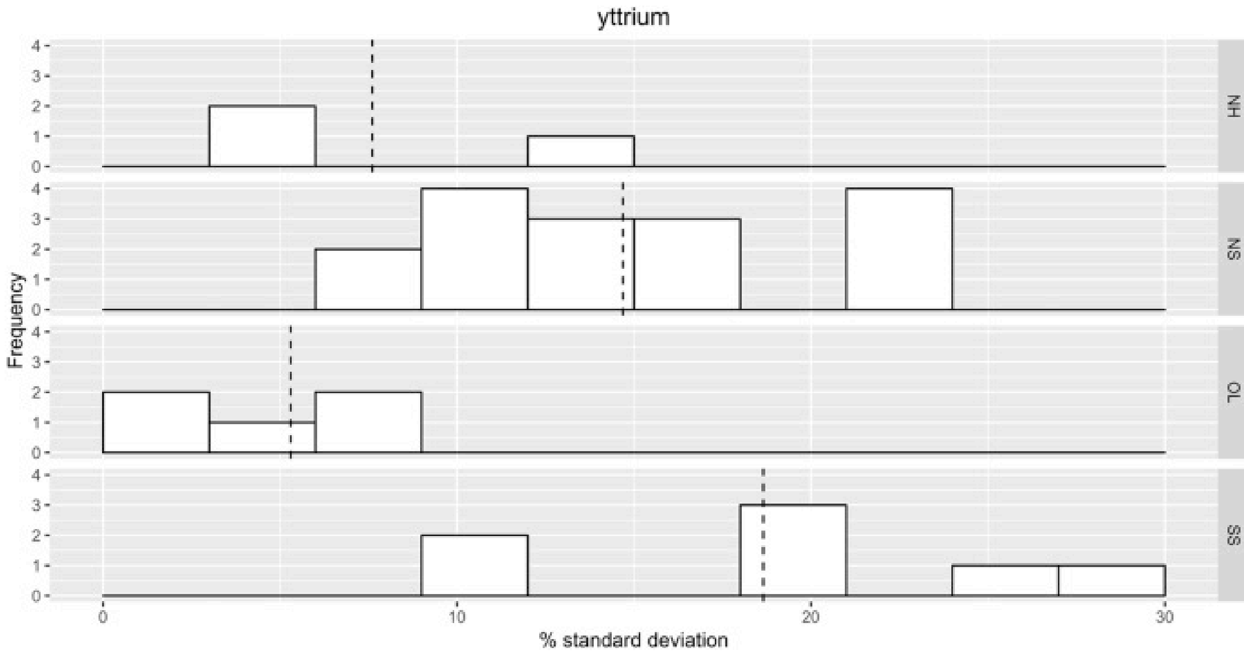

Figure 12. Histograms of % standard deviation for yttrium by granulite outcrop. Abbreviations: NH = Naisiusiu Hill; NS = Naibor Soit; OL = Oldoinyo Okule; SS = Shifting Sand. Vertical dashed line indicates the mean value for each outcrop.

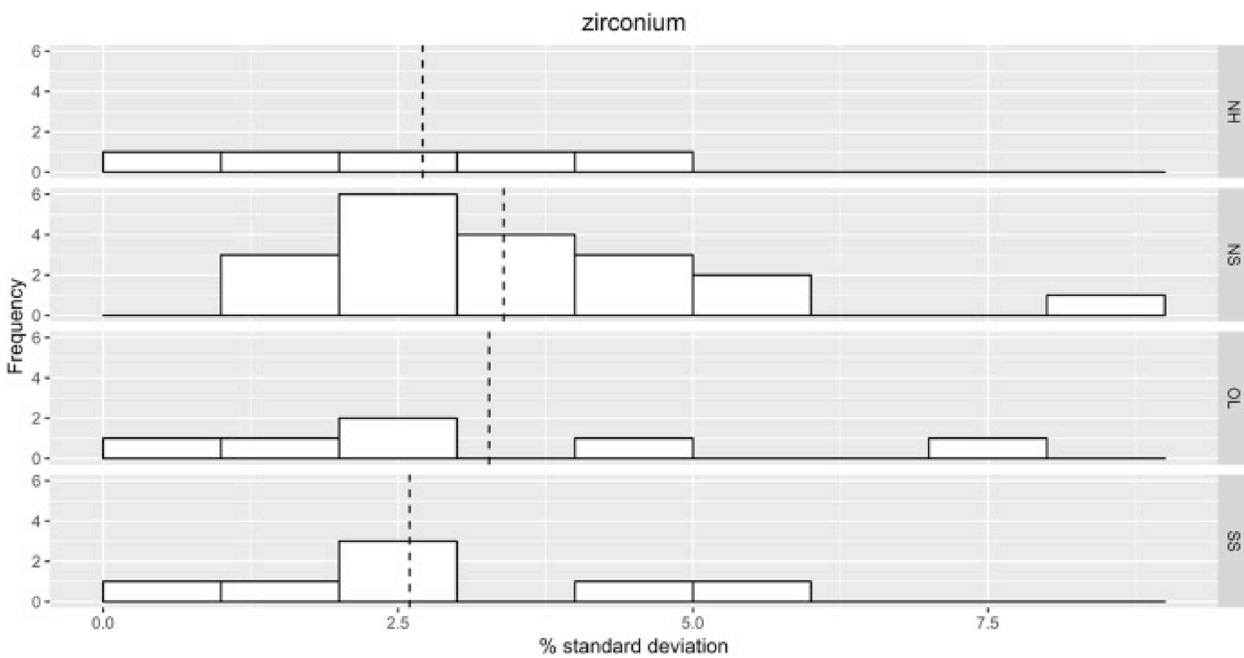

Figure 13. Histograms of % standard deviation for zirconium by granulite outcrop. Abbreviations: NH = Naisiusiu Hill; NS = Naibor Soit; OL = Oldoinyo Okule; SS = Shifting Sand. Vertical dashed line indicates the mean value for each outcrop.

3.3. Validity of pXRF data

Mood's median tests indicate significant differences in elemental composition, and post-hoc tests uncover some interesting patterns (Table 6). Oldoinyo Okule appears to be chemically distinct from many of the other sources, whereas Naisiusiu Hill shows comparatively few significant differences. We thus expect Oldoinyo Okule to be more readily distinguished, and Naisiusiu Hill much less so, from the other sources. The elements that most frequently differ significantly among the outcrops are titanium, iron, and yttrium. Unfortunately, treating the Naibor Soit hills as separate sources results in considerably reduced predictive performance. We therefore combine all three hills into a single source for the purposes of predictive modeling.

Table 6. p-values of Mood's median post-hoc tests for each pair of granulite outcrops[a,b,c].

	Element						
Pair	**K**	**Ti**	**Fe**	**Sr**	**Y**	**Zr**	**# sig. differences**
NS-M/NH	0.17	0.46	1.00	0.69	0.64	1.00	0
NS-MH/NH	0.11	**0.00**	**0.00**	1.00	**0.00**	0.25	3
NS-SO/NH	**0.00**	0.09	**0.03**	0.25	**0.00**	0.10	3
OL/NH	0.11	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	5
SS/NH	**0.00**	0.80	0.06	**0.04**	0.27	0.66	2
NS-MH/NS-M	0.32	**0.00**	**0.00**	0.85	0.10	0.51	2
NS-SO/NS-M	0.23	0.09	**0.00**	0.25	**0.00**	0.08	2
OL/NS-M	0.80	**0.00**	**0.02**	**0.00**	**0.00**	**0.01**	4
SS/NS-M	**0.00**	0.39	0.19	0.09	0.39	0.28	1
NS-SO/NS-MH	**0.00**	**0.00**	**0.00**	**0.04**	0.79	0.10	4
OL/NS-MH	0.23	**0.00**	0.22	**0.00**	**0.00**	**0.00**	4
SS/NS-MH	**0.00**	**0.00**	**0.00**	0.12	0.27	**0.01**	4
OL/NS-SO	0.23	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	4
SS/NS-SO	**0.00**	**0.01**	**0.00**	**0.00**	**0.00**	**0.00**	6
SS/OL	**0.00**	**0.00**	0.24	**0.00**	**0.00**	**0.00**	5
# sig. differences	7	10	10	8	9	7	

[a] Tests with significant values at the p = 0.05 level are in bold.
[b] p-values for multiple comparisons are adjusted using Benjamani and Hochberg's (1995) method.
[c] See Table 1 for abbreviations.

Table 7 summarizes the performance of each model for the testing set and the entire dataset. The least biased evaluation of model performance, that of the testing set, yields accuracy values of 75%–80%. Prediction accuracy for the entire granulite dataset, which includes those specimens used to build the models, ranges between 72% and 94%. While the SVM and RF models tend to predict with the highest accuracy, all the models perform significantly better than chance. As expected, specimens from Naisiusiu Hill are predicted with the lowest overall accuracy. Low sensitivity is largely responsible for this pattern, however, as the models have difficulty correctly assigning the Naisiusiu Hill specimens to the correct outcrop. The specificity scores, on the other hand, are very high. The models are therefore much better at identifying the specimens that *do not* derive from Naisiusiu Hill than they are at identifying the specimens that *do* derive from Naisiusiu Hill. Sensitivity, specificity, and balanced accuracy among the other outcrops are ≥72% and frequently exceed 90%. These results are most easily visualized through the LDA model (Fig. 14), which produces a three-function solution where the first function achieves 66.4%, the second 25.8%, and the third 9.8% of the separation among outcrops in the training set. Oldoinyo Okule again appears as the most chemically distinct outcrop, while a good deal of overlap exists between Naisiusiu Hill and the other outcrops, especially Naibor Soit. This pattern also helps explain the higher accuracy scores of the SVM and RF models, which, unlike LDA, are not constrained by linear combinations of predictors for classification.

Table 7. Performance of predictive models.

Model	Accuracy	Kappa	Outcrop	Sensitivity	Specificity	Balanced accuracy
Testing set						
LDA	0.759	0.632	NH	0.125	0.957	0.541
			NS	0.885	0.750	0.817
			OL	0.889	0.911	0.900
			SS	0.818	1.000	0.909
MDA	0.778	0.657	NH	0.125	0.957	0.541
			NS	0.923	0.750	0.837
			OL	0.889	0.933	0.911
			SS	0.818	1.000	0.909
SVM	0.796	0.684	NH	0.125	1.000	0.563
			NS	0.923	0.750	0.837
			OL	1.000	0.956	0.978
			SS	0.818	0.954	0.886
kNN	0.754	0.629	NH	0.368	0.973	0.671
			NS	0.810	0.963	0.793
			OL	0.810	0.933	0.886
			SS	0.852	0.903	0.877
RF	0.796	0.700	NH	0.250	0.957	0.603
			NS	0.885	0.929	0.907
			OL	1.000	0.956	0.978
			SS	0.818	0.884	0.851
Entire dataset						
LDA	0.723	0.577	NH	0.222	0.955	0.589
			NS	0.820	0.716	0.768
			OL	0.833	0.948	0.891
			SS	0.763	0.938	0.851
MDA	0.788	0.681	NH	0.370	0.975	0.672
			NS	0.832	0.790	0.811
			OL	0.900	0.961	0.818
			SS	0.895	0.938	0.917
SVM	0.815	0.717	NH	0.370	0.994	0.682
			NS	0.910	0.790	0.850
			OL	0.900	0.968	0.934
			SS	0.842	0.945	0.894
kNN	0.739	0.609	NH	0.259	0.975	0.617
			NS	0.798	0.779	0.788
			OL	0.887	0.942	0.904
			SS	0.842	0.904	0.873
RF	0.940	0.912	NH	0.779	0.987	0.883
			NS	0.966	0.979	0.973
			OL	1.000	0.987	0.994
			SS	0.947	0.966	0.957

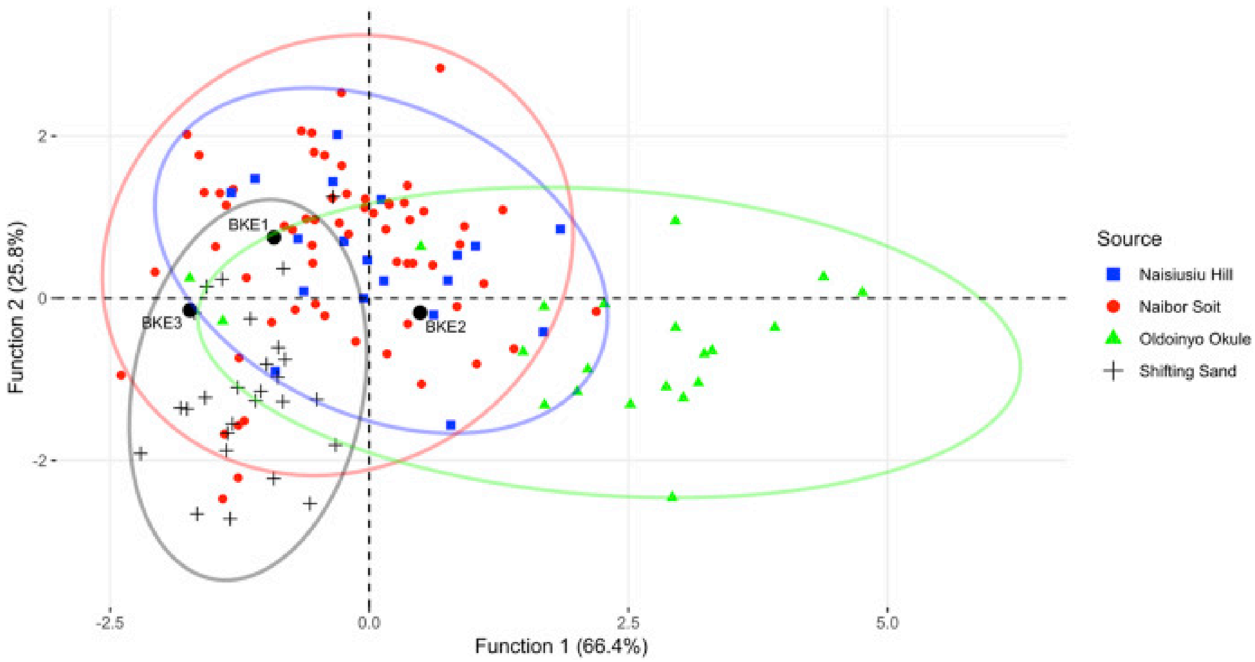

Figure 14. LDA plot of the granulite testing set (n = 130) with 95% confidence ellipses (that is, the mean scores of each source on the first two discriminant functions lie within the ellipse 95% of the time). The three artifacts from BK East are identified by black dots.

3.4. Artifact source assignments

Two of the five analyzed artifacts are missing values for one or two of the predictor elements and therefore cannot be assigned to a source by the predictive models. Table 8 summarizes the discrete (i.e., outcrop) and continuous (i.e., posterior probability) predictions for the three remaining BK East artifacts (see also Fig. 14). Specimen BKE1 is predicted by all the models to derive from Naibor Soit with probabilities ranging from 0.57 (kNN) to 0.92 (LDA). Specimen BKE2 is assigned by LDA, MDA, SVM, and kNN to Naibor Soit with probabilities ranging from 0.71 (kNN) to 0.98 (MDA) and by RF to Shifting Sand with a probability of 0.45. Specimen BKE3 is the least securely identified, with assignments by LDA, MDA, and SVM to Naibor Soit with a probability of ~0.65 and by kNN and RF to Shifting Sand with probabilities of 0.43 and 0.50, respectively. The Naibor Soit inselbergs lie approximately four kilometers away from BK East, while Shifting Sand requires a trek of approximately six kilometers.

Table 8. Predicted sources of metamorphic artifacts from BK East.

	Predicted source (probability of source identification)					
Specimen	**LDA**	**MDA**	**SVM[a]**	**kNN**	**RF**	**Overall**
BKE1	NS (0.92)	NS (0.88)	NS (NA)	NS (0.57)	NS (0.87)	NS (0.81)
BKE2	NS (0.87)	NS (0.98)	NS (NA)	NS (0.71)	SS (0.45)	NS (0.85)/SS (0.45)
BKE3	NS (0.65)	NS (0.64)	NS (NA)	NS (0.43)/SS (0.43)	SS (0.50)	NS (0.57)/SS (0.47)

[a] SVM models do not directly generate posterior probabilities (Kuhn and Johnson, 2014: 348).

3.5. Rebound hardness

Fig. 15, Fig. 16 display boxplots by source and rock type, respectively. Mood's median tests indicate that hardness values differ significantly among sources ($\chi^2 = 49.21$; df = 6; $p < 0.01$) and raw material type ($\chi^2 = 33.80$; df = 2; $p < 0.01$). Post-hoc comparisons reveal that rocks from the Kelogi Hills show significantly lower hardness values, and those from Lemagurut significantly higher hardness values, than rocks from the other sources (Table 9). When examined by rock type, the fine-grained volcanic rocks from Lemagurut and Engelosin show the highest hardness values, the granulites from Naibor Soit, Naisiusiu Hill, Oldoinyo Okule, and Shifting Sand intermediate hardness values, and the gneisses from the Kelogi Hills the lowest hardness values (Table 10). Shifting Sand and the Kelogi Hills exhibit the most variation in hardness, whereas the other outcrops have much tighter ranges of variation. When rock types are combined, the fine-grained volcanics and granulites show much less variation in hardness than the coarser-grained gneisses.

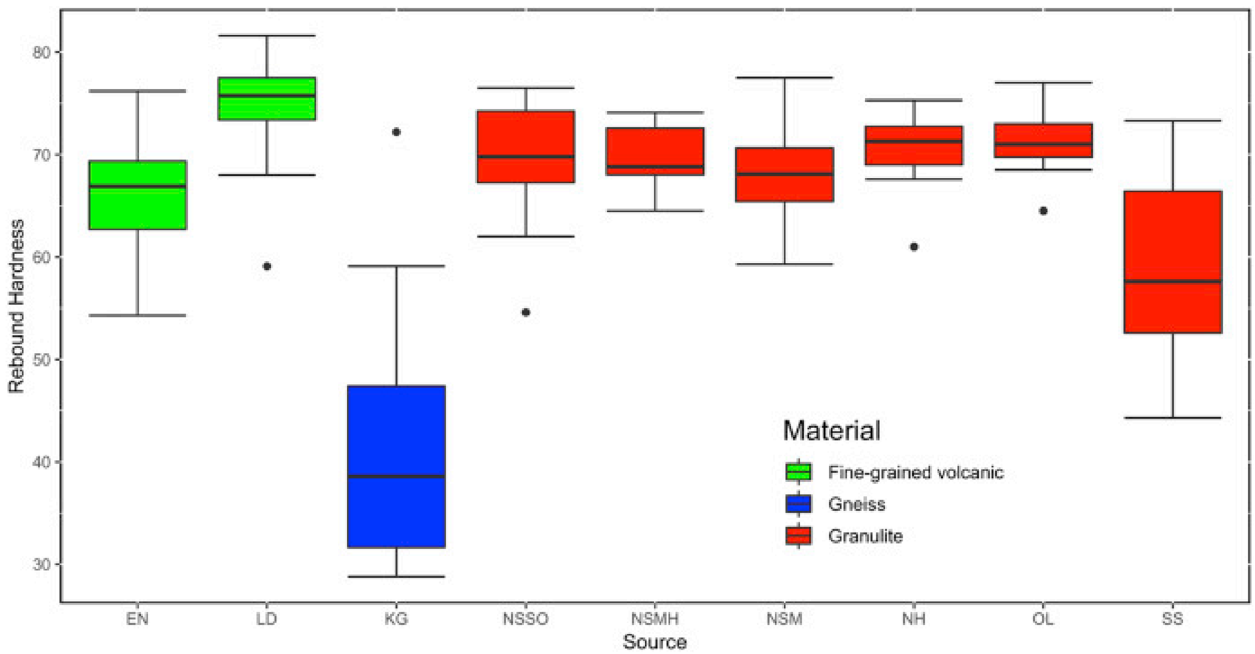

Figure 15. Boxplots of rebound hardness by source. Abbreviations: EN = Engelosin; LD = Lemagurut Drainage; KG = Kelogi Hills; NSSO = Naibor Soit Southern Outlier; NSMH = Naibor Soit Manyata Hill; NSM = Naibor Soit Main Hill; NH = Naisiusiu Hill; OL = Oldoinyo Okule; SS = Shifting Sand.

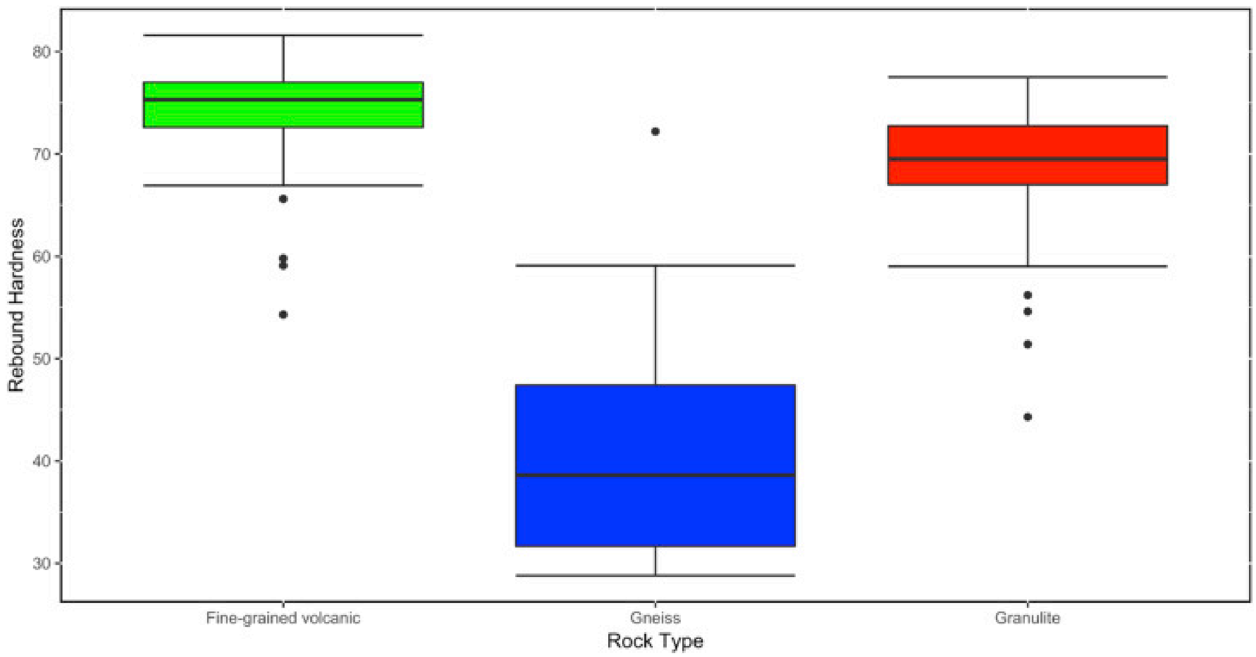

Figure 16. Boxplots of rebound hardness by rock type.

Table 9. p-values of rebound hardness Mood's median post-hoc tests for each pair of sources[a,b,c].

		Source					
		EN	KG	LD	NH	NS	OL
Source	KG	**0.01**					
	LD	0.17	**0.00**				
	NH	0.43	**0.01**	**0.03**			
	NS	0.50	**0.01**	**0.00**	0.50		
	OL	0.69	**0.01**	**0.00**	1.00	0.11	
	SS	0.69	0.10	**0.05**	0.17	0.69	0.47

[a] Tests with significant values at the p = 0.05 level are in bold.
[b] p-values for multiple comparisons are adjusted using Benjamani and Hochberg's (1995) method.
[c] Abbreviations: KG = Kelogi Hills; LD = Lemagarut Drainages; NH = Naisiusiu Hill; NS = Naibor Soit; OL = Oldoinyo Okule; SS = Shifting Sand.

Table 10. p-values of rebound hardness Mood's median post-hoc tests for each pair of raw material types[a,b,c].

		Raw material	
		FGV	GN
Raw material	GN	**0.00**	
	GR	**0.00**	**0.01**

[a] Tests with significant values at the p = 0.05 level are in bold.
[b] p-values for multiple comparisons are adjusted using Benjamani and Hochberg's (1995) method.
[c] Abbreviations: FGV = fine-grained volcanic (Engelosin and Lemagurut); GN = gneiss (Kelogi Hills); GR = granulite (Naibor Soit, Naisiusiu Hill, Shifting Sand, Oldoinyo Okule).

4. Discussion

4.1. Raw material sourcing in the Olduvai Basin

There is moderate to good agreement between the NIST element concentrations and those derived from pXRF, and if we consider the former to be the "true" values, the latter are reasonably geochemically accurate. In the future, the factory-set pXRF calibration can be adjusted, with the use of additional SRMs, to achieve greater accuracy. With some exceptions, particularly among the Naibor Soit hills, the pXRF instrument also produces highly repeatable measurements. We thus consider the pXRF-derived element concentrations to be reliable input for the predictive models. If we acknowledge that statistical approaches to classification involve some uncertainty, a method's validity should be gauged by its ability to link isolated rocks correctly to their known sources at rates well above chance. By this statistical standard, the protocol outlined here is valid for sourcing rocks to four major granulite outcrops (Naisiusiu Hill, Shifting Sand, Oldoinyo Okule, and Naibor Soit) in the Olduvai Basin.

Using LDA and leave-one-out cross-validation on desktop XRF and pXRF data, Abtosway (2018) reports classification accuracies ranging from ~50% to ~90% for rocks from Naibor Soit, Shifting Sand, and Naisiusiu Hill. The desktop XRF data outperform those of the pXRF, likely because of the former's superior ability to detect trace concentrations for those elements most able to distinguish among outcrops. He cautions, however, that the LDA results may be biased due to severe class imbalances and small sample size (between four and 27 per outcrop in this case). The results presented here indicate that larger samples can consistently produce classification accuracies of ~75%–80%. This is significant given that an artifact's source must first be identified before the rebound data can be applied to archaeological specimens that cannot be subjected to the impact of a rebound hammer.

To evaluate the results for the BK East artifacts, we consider the most frequently predicted source (Naibor Soit in all cases) to be the "final" identification. Luedtke (1979: 750–751) distinguishes three types of error in the identification of artifacts to a particular source. A Type 1 error is the assignment of an artifact to a sampled source when it actually derives from another sampled source. This does not appear to be the case with BKE1: not only is it invariably assigned to Naibor Soit, but the models do so with a mean probability of 0.81. A Type 1 error for BKE2 is possible but seems unlikely given that four out of five models identify it to Naibor Soit with a mean probability of 0.85. The identification of BKE3 is the most likely Type 1 error candidate, as only three out of five models assign it to Naibor Soit (mean probability = 0.57). The next most likely source for this artifact is Shifting Sand.

A Type 2 error occurs when an artifact is predicted to derive from an unsampled source when it in fact derives from a sampled source. The models obviously cannot formally assign an artifact to an unsampled source. However, what if low posterior probabilities—say, 0.25, which is the lowest possible value that can be shared among four classes—are associated with all the sampled sources? We might incorrectly interpret this to mean that an artifact derives from an unsampled source. The models are confident in their attribution of BKE1 and BKE2 to a sampled source, so a Type 2 error is unlikely for these two artifacts. BKE3, on the other hand, shows lower posterior probabilities even for the two most likely sampled sources. This artifact might then be incorrectly interpreted as deriving from an unsampled source.

Type 3 errors arise if an artifact that actually derives from an unsampled source is incorrectly identified as a member of a sampled source. If Jones (1994: 254) is correct that "we possess the unusual advantage of knowing the exact sources of all the major types of lithic raw materials that were used by early tool makers" at Olduvai, then we can effectively dismiss the possibility of Type 3 errors. However, while BKE3 is predicted to derive from either Naibor Soit or Shifting Sand, the probabilities of class membership are not particularly high. Even the BKE1 and BKE2 artifacts are susceptible to this error if there is an unsampled source that mimics (at least statistically) the geochemical signature of Naibor Soit. Such a source may exist, either buried beneath the basin's Late Pleistocene and Holocene sediments or among the handful of currently exposed primary metamorphic outcrops that lie farther away from the gorge and outside the sampling area of our study (Hay, 1976; Blumenschine et al., 2008; Favreau, 2019). The identification with high probabilities of two BK East artifacts to Naibor Soit nevertheless supports the long-held notion that this inselberg served as a source of toolstone throughout the early Pleistocene (L.S.B. Leakey, 1951, M.D. Leakey, 1971; Hay, 1976; Potts, 1984; Blumenschine et al., 2008).

Other lines of macroscopic and petrochemical evidence can help further refine source assignments. Rocks from Naibor Soit and Naisiusiu Hill can often be distinguished based on grain size and the density of muscovite features (Hay, 1976; Tactikos, 2005; McHenry and de la Torre, 2018). While Favreau (2019), who focuses on thin-section petrography, finds grain size to be an ambiguous indicator of source, he does identify modal mineralogies among Olduvai's quartz-rich outcrops, some of which appear to be unique to pairs of outcrops or even single outcrops. Unfortunately, such precision often requires destructive techniques, which limit or preclude applications to artifacts. Non-destructive pXRF remains relevant in this context if geochemical correlates for outcrop-specific mineralogical features can be identified (Favreau, 2019: 158). This is a worthwhile endeavor given the presence of quartz-rich metamorphic artifacts at several Bed II sites that either appear in cobble form (indicating a secondary, probably fluvial, source) or do not seem to exhibit the features of Naibor Soit (de la Torre, 2004; Diez-Martín et al., 2009; Santonja et al., 2014, 2018; Rubio-Jara et al., 2017; McHenry and de la Torre, 2018).

4.2. Raw material suitability in the Olduvai Basin

Kyara (1999: 248) offers a comprehensive list of potentially relevant attributes that may have conditioned hominin raw material selection in the Olduvai Basin, including flakability, accessibility, utility, and nodule size and morphology along with less commonly cited properties like ease of extraction, portability, moisture absorption, and weathering. While hominins possibly considered many or all of these, we deem fracture predictability to be particularly important because the execution of a reduction strategy requires some knowledge of how stone will fracture upon impact (Jones, 1994; Brantingham et al., 2000; Brantingham, 2010; Gurtov and Eren, 2014), though implementation also depends on the knapper's skill-level (Eren et al., 2011).

Rebound hardness results suggest that Kelogi gneiss fractures very unpredictably. These quantitative data echo qualitative observations that these rocks are "friable" (Tactikos, 2005: 70), of "poor quality" (Kimura, 1997: 87) and, in terms of flaking, are "not easily controllable" (Kyara, 1999: 151). They are, in other words, unsuitable for the consistent production of complete, sharp flakes. The granulites from Naibor Soit, Naisiusiu Hill, Shifting Sand, and

Oldoinyo Okule and the Engelosin phonolites show intermediate rebound hardness values. The basalts from Lemagurut show the highest rebound hardness values. Again, this matches well with experimental work that demonstrates the unpredictability of fracture among Naibor Soit rocks relative to Olduvai's harder and more predictably fractured basalts (Jones, 1981, 1994; Kyara, 1999; Tactikos, 2005; Diez-Martín et al., 2011; Reti, 2013; Gurtov and Eren, 2014; Gurtov et al., 2015; Sánchez-Yustos et al., 2015; Byrne et al., 2016). We should thus expect that the knapping of basalts produces higher relative frequencies of complete flakes than does the knapping of rocks from Naibor Soit, which is indeed the case (Reti, 2013: 142; see also Kyara, 1999: 277). Although most work focuses on Naibor Soit, we might also anticipate that mineralogical and textural variation results in differences in fracture predictability between granulite outcrops. Tactikos (2005: 160, 240), for example, finds that the finer-grained Naisiusiu Hill rocks are less susceptible to shattering (and, in our terminology, potentially more suitable for the production of complete flakes) than those of Naibor Soit. The rebound hardness data do capture this distinction, although with the exception of the Kelogi Hills, the median values among the metamorphic outcrops are not statistically significantly different.

The correspondence of rebound hardness to informal impressions and experimental observations suggests that it is a valid measure of suitability as defined here. We can thus use ratio-scale data to compare suitability across outcrops and rock types more easily and directly. The rebound hardness data reveal a particularly interesting attribute that can be difficult to capture with qualitative measures of rock suitability, namely variation *within* outcrops and rock types. Take gneiss for instance, which is relatively rare among the Bed I and II lithic assemblages at Olduvai (Leakey, 1971; Potts, 1988; Kyara, 1996; Kimura, 1999, 2002; de la Torre and Mora, 2005). This pattern is reasonably interpreted to reflect hominins' awareness of this material's poor suitability for tool manufacture (Kyara, 1999). However, the rebound hardness data indicate that it is not impossible to encounter a stone suitable for knapping from the Kelogi Hills—indeed, we have LCTs knapped from this material from SHK (Sánchez-Yustos et al., 2019)–only that it is extremely unlikely. Contrast this with the basalts, where the chances are good that a suitable piece of stone can be found regardless of where in the drainages one looks. Put another way, foraging for suitable toolstone involves more guesswork at highly variable sources like the Kelogi Hills. All else being equal, it may be that hominins were sensitive to intra-source variability in suitability rather than the suitability of a rock type *per se*. This proposition could be explored with Shifting Sand. While the median rebound hardness for this outcrop is not significantly different from that of the other metamorphic outcrops, the variation around that median is much greater. So, even though the rocks from Shifting Sand are, on average, just as suitable as those from any other granulite outcrop, there is still considerable risk of not finding a suitable stone there. If this factored into hominin raw material selection, and if quartz-rich metamorphic artifacts from Olduvai can be reliably sourced, we might expect pieces from Shifting Sand to be quite rare, even at archaeological sites close to the outcrop.

Our focus on fracture predictability by no means implies that this measure of raw material suitability was of paramount, or even ancillary, importance to hominin knappers in the paleo-Olduvai Basin. Our data in fact confirm that the preponderance of flakes made from metamorphic rocks and the concomitant paucity of flakes made from basalt and other fine-grained volcanic rocks at many Bed I and II sites (Leakey, 1971; Potts, 1988; Kimura, 1997, 1999; de la Torre and Mora, 2005) reflects a bias *against* predictably fractured stones for flake manufacture. Practical experience with the basin's raw materials helps explain this pattern. For one, fine-grained volcanic rocks typically occur as rounded cobbles that lack the angles required to initiate flaking (de la Torre and Mora, 2018). What is more, Jones (1981: 191) and others (Kyara, 1999: 309, 361; Gurtov and Eren, 2014: 290; McHenry and de la Torre, 2018: 399) report that considerably more energy is required to remove flakes from volcanic rocks, especially basalts, than is required to remove flakes from granulite slabs. Durability also appears to play an important role: during carcass butchery and wood-working activities, the edges of flakes made from volcanics, particularly phonolite, tend to blunt more rapidly than do those made from granulite sources (Jones, 1979: 835–836, 1980: 158, 1994: 257, 292–294; Tactikos, 2005: 243; Sánchez-Yustos et al., 2016). Finally, the basin's friable granulites are ideal for bipolar reduction, an expedient technique that requires little skill and yet quickly and easily produces numerous useable flakes (Gurtov and Eren, 2014). At some sites, Olduvai hominins nevertheless appear to have intentionally selected predictably fractured rocks for the manufacture of LCTs (Kyara, 1999; de la Torre and Mora, 2018).

5. Conclusions

Coupling pXRF-derived element concentrations with multivariate predictive modeling is a valid method for classifying metamorphic rocks in the Olduvai Basin. This protocol identifies Naibor Soit as the most likely source for three metamorphic artifacts from the upper Middle Bed II deposits at BK East. It should be stressed, however—and this applies to *any* sourcing method—that the combination of attributes (a specific inventory of element concentrations) and source assignment procedures (specific classes of multivariate predictive models) we use here is not necessarily valid in other contexts. After all, every region of archaeological interest contains a unique assemblage of rock types that (may) require a distinctive approach to raw material group detection and assignment. Occasionally, Weigand et al.'s (1977: 24) "provenience postulate" simply may not hold, in which case source assignments are impossible or result in unacceptably high error rates. The Olduvai pXRF data are promising in this context, but we do not intend for them to stand on their own. Lithic sourcing, like any provenience study, benefits from the application of multiple methods (e.g., Braun et al., 2008, 2009a; McHenry and de la Torre, 2018).

Fracture predictability is generally considered to be an important factor in the selection of lithic raw materials during the ESA. Rebound hardness is a ratio-scale measure that correlates strongly with fracture predictability (Noll, 2000; Braun et al., 2009b) and, as such, can facilitate intra- and inter-source comparisons. Clear associations exist among major rock types in the Olduvai Basin: fine-grained volcanic rocks show higher hardness values than do metamorphic rocks. Interesting patterns also emerge within rock types and even within single outcrops. Engelosin phonolite, for instance, shows slightly lower, and more variable, hardness values than the Lemagurut basalts. Likewise, the rocks from Shifting Sand are much more variable in terms of hardness than those from other granulite outcrops. The most variation in hardness is found within the gneiss of the Kelogi Hills. Whether these intra-source patterns influenced hominin raw material selection remains to be seen. What is evident is that predictably fractured rocks were often ignored in favor of less predictably fractured ones, particularly for flake production.

Due to its complex geological history, the Olduvai Basin is home to a wide variety of rock types and forms. This is undoubtedly one of the reasons it was able to support early Pleistocene hominin populations whose cultures, after all, involved the manufacture and use of stone tools. The presence of such a diverse reservoir of knappable rocks within a geographically circumscribed area enables a detailed examination of hominin raw material proclivities. Little wonder, then, that raw material availability and suitability factor significantly in the formal land-use models offered by Potts (1982, 1988, 1991), Blumenschine and colleagues (1998; 2008, 2012), and Tactikos (2005). As scholars evaluate these and other models, we need to continue to integrate fine-grained paleoecological reconstructions with reliable sourcing data and objective measures of raw material suitability.

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